Measurement device independent quantum key distribution

Hoi-Kwong Lo¹, Marcos Curty², and Bing Qi¹

¹Center for Quantum Information and Quantum Control,

Dept. of Electrical & Computer Engineering and Dept. of Physics,

University of Toronto, Toronto, Ontario, M5S 3G4, Canada

²Escuela de Ingeniería de Telecomunicación, Dept. of Signal Theory and Communications,

University of Vigo, Vigo, Pontevedra, 36310, Spain

(Dated: May 30, 2012)

How to remove detector side channel attacks has been a notoriously hard problem in quantum cryptography. Here, we propose a simple solution to this problem—measurement device independent quantum key distribution. It not only removes all detector side channels, but also doubles the secure distance with conventional lasers. Our proposal can be implemented with standard optical components with low detection efficiency and highly lossy channels. In contrast to the previous solution of full device independent QKD, the realization of our idea does not require detectors of near unity detection efficiency in combination with a qubit amplifier (based on teleportation) or a quantum non-demolition measurement of the number of photons in a pulse. Furthermore, its key generation rate is many orders of magnitude higher than that based on full device independent QKD. The results show that long-distance quantum cryptography over say 200km will remain secure even with seriously flawed detectors.

Quantum key distribution (QKD) allows two parties (typically called Alice and Bob) to generate a common string of secret bits, called a secret key, in the presence of an eavesdropper, Eve [1]. This key can be used for tasks such as secure communication and authentication. Unfortunately, there is a big gap between the theory and practice of QKD. In principle, QKD offers unconditional security guaranteed by the laws of physics [2–4]. However, real-life implementations of QKD rarely conform to the assumptions in idealized models used in security proofs. Indeed, by exploiting security loopholes in practical realizations, especially imperfections in the detectors, different attacks have been successfully launched against commercial QKD systems [5, 6], thus highlighting their practical vulnerabilities.

To connect theory with practice again, several approaches have been proposed. The first one is the presumably hard-verifiable problem of trying to characterize real devices fully and account for all side channels. The second approach is a teleportation trick [2, 7]. The third solution is (full) device independent QKD (DI-QKD) [9]. This last technique does not require detailed knowledge of how QKD devices work and can prove security based on the violation of a Bell inequality. Unfortunately, DI-QKD is highly impractical because it needs near unity detection efficiency together with a qubit amplifier or a quantum non-demolition (QND) measurement of the number of photons in a pulse, and even then generates an extremely low key rate (of order 10^{-10} bits per pulse) at practical distances [10].

In this Letter we present the idea of measurement device independent QKD (MDI-QKD) as a simple solution to remove all (existing and yet to be discovered) detector side channels [6], arguably the most critical part of the implementation, and show that it has both excellent security and performance. Therefore, it offers an immense security advantage over standard security proofs such as

Inamori-Lütkenhaus-Mayers (ILM) [11] and Gottesman-Lo-Lütkenhaus-Preskill (GLLP) [12]. Furthermore, it has the power to double the transmission distance that can be covered by those QKD schemes that use conventional laser diodes, and its key generation rate is comparable to that of standard security proofs with entangled pairs. In contrast to DI-QKD, in its simplest formulation MDI-QKD requires the additional assumption that Alice and Bob have almost perfect state preparation. However, we believe that this is only a minor drawback because Alice's and Bob's signal sources can be attenuated laser pulses prepared by themselves. Their states can thus be experimentally verified in a fully protected laboratory environment outside Eve's interference through random sampling. Moreover, as will be discussed later, imperfections in Alice's and Bob's preparation process can, in fact, be readily taken care of in a more refined formulation of the protocol.

A simple example of our method is as follows. Both Alice and Bob prepare phase randomized weak coherent pulses (WCPs) in the four possible BB84 polarization states [13] and send them to an untrusted relay Charlie (or Eve) located in the middle, who performs a Bell state measurement that projects the incoming signals into a Bell state [14]. Such measurement can be realized, for instance, using only linear optical elements with say the setup given in Fig. 1. (Actually, such setup only identifies two of the four Bell states. But, this is fine as any Bell state will allow a security proof to go through.) Furthermore, Alice and Bob apply decoy state techniques [15] to estimate the gain (i.e., the probability that the relay outputs a successful result) and quantum bit error rate (QBER) for various input photon numbers.

Once the quantum communication phase is completed, Charles uses a public channel to announce the events where he has obtained a successful outcome in the relay, including as well his measurement result. Alice and

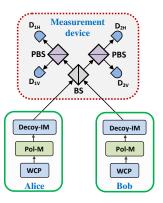


FIG. 1. Basic setup of a MDI-QKD protocol. Alice and Bob prepare phase randomized weak coherent pulses (WCPs) in a different BB84 polarization state which is selected, independently and at random for each signal, by means of a polarization modulator (Pol-M). Decoy states are generated using an intensity modulator (Decoy-IM). Inside the measurement device, signals from Alice and Bob interfere at a 50:50 beam splitter (BS) that has on each end a polarizing beam splitter (PBS) projecting the input photons into either horizontal (H) or vertical (V) polarization states. Four single-photon detectors are employed to detect the photons and the detection results are publicly announced. A successful Bell state measurement corresponds to the observation of precisely two detectors (associated to orthogonal polarizations) being triggered. A click in D_{1H} and D_{2V} , or in D_{1V} and D_{2H} , indicates a projection into the Bell state $|\psi^{-}\rangle = 1/\sqrt{2}(|HV\rangle - |VH\rangle),$ while a click in D_{1H} and D_{1V} , or in D_{2H} and D_{2V} , reveals a projection into the Bell state $|\psi^{+}\rangle = 1/\sqrt{2}(|HV\rangle + |VH\rangle)$. Alice's and Bob's laboratories are well shielded from the eavesdropper, while the measurement device can be untrusted.

Bob keep the data that correspond to these instances and discard the rest. Moreover, as in BB84, they post-select the events where they use the same basis in their transmission by means of an authenticated public channel. Finally, to guarantee that their bit strings are correctly correlated, either Alice or Bob has to apply a bit flip to her/his data, except for the cases where both of them select the diagonal basis and Charles obtains a successful measurement outcome corresponding to a triplet state. This is illustrated in Table 1.

Alice & Bob	Relay output $ \psi^-\rangle$	Relay output $ \psi^+\rangle$
Rectilinear basis	Bit flip	Bit flip
Diagonal basis	Bit flip	=

TABLE I. Alice and Bob post-select the events where the relay outputs a successful result and they use the same basis in their transmission. Moreover, either Alice or Bob flips her/his bits except for the cases where both of them select the diagonal basis and the relay outputs a triplet.

Let us now evaluate the performance of the protocol above in detail. The proof of its unconditional security is shown in Appendix A. For simplicity, we consider a refined data analysis where Alice and Bob evaluate the data sent in two bases *separately* [16]. In particular, we

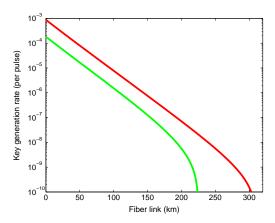
use the rectilinear basis as the key generation basis, while the diagonal basis is used for testing only. A piece of notation: Let us denote by $Q_{\rm rect}^{n,m}$, $Q_{\rm diag}^{n,m}$, $e_{\rm rect}^{n,m}$ and $e_{\rm diag}^{n,m}$, the gain and QBER, respectively, of the signal states sent by Alice and Bob, where n and m denote the number of photons sent by the legitimate users, and rect/diag represents their basis choice.

- (A) Rectilinear basis: An error corresponds to a successful relay output when both Alice and Bob prepare the same polarization state (i.e., their results should be anti-correlated before they apply a bit flip). Assuming for the moment ideal optical elements and detectors, and no misalignment, we have that whenever Alice and Bob send, respectively, n and m photons prepared in the same polarization state the relay will never output a successful result. We obtain then that $e_{\text{rect}}^{n,m}$ is zero for all n, m. This means that no error correction is needed for the sifted key. This is remarkable because it implies that the usage of WCP sources (rather than single-photon sources) does not substantially lower the key generation rate of the QKD protocol (in the error correction part).
- (B) Diagonal basis: To work out the amount of privacy amplification needed we examine the diagonal basis. An error corresponds to a projection into the singlet state given that Alice and Bob prepared the same polarization state, or into the triplet state when they prepare orthogonal polarizations. Assuming again the ideal scenario discussed in the previous paragraph, we find that $e_{\text{diag}}^{1,1} = 0$. (This is because when two identical single-photons enter a 50:50 BS the Hong-Ou-Mandel (HOM) effect [17] ensures that both photons will always exit the BS together in the same output mode. Also, if the two photons are prepared in orthogonal polarizations and they exit the 50:50 BS in the same output arm, both photons will always reach the same detector within the relay.) The fact that $e_{
 m diag}^{1,1}$ is zero is again remarkable as it means that the usage of WCP sources does not substantially lower the key generation (in also the privacy amplification part).
- (C) Key generation rate: In the ideal scenario described above the key generation rate will be simply given by $R = Q_{\text{rect}}^{1,1}$ in the asymptotic limit of an infinitely long key. On the other hand, if we take imperfections such as basis misalignment and dark counts into account, the key generation rate in a realistic setup will be given by [12, 16, 18]

$$R = Q_{\text{rect}}^{1,1}[1 - H(e_{\text{diag}}^{1,1})] - Q_{\text{rect}}f(E_{\text{rect}})H(E_{\text{rect}}), \quad (1)$$

where $Q_{\rm rect}$ and $E_{\rm rect}$ denote, respectively, the gain and QBER in the rectilinear basis (i.e., $Q_{\rm rect} = \sum_{n,m} Q_{\rm rect}^{n,m}$, and $E_{\rm rect} = \sum_{n,m} Q_{\rm rect}^{n,m} e_{\rm rect}^{n,m}/Q_{\rm rect}$), $f(E_{\rm rect}) > 1$ is an inefficiency function for the error correction process, and $H(x) = -x \log_2(x) - (1-x) \log_2(1-x)$ is the binary Shannon entropy function.

There are few loose ends that need to be tightened up. First, we have implicitly assumed that the decoy state method can be used to estimate the gain $Q_{\rm rect}^{1,1}$ and the QBER $e_{\rm diag}^{1,1}$. Second, we need to evaluate the se-



Lower bound on the secret key rate R given by Eq. (1) in logarithmic scale for the MDI-QKD setup with WCPs illustrated in Fig. 1 (green curve). For simulation purposes, we consider the following experimental parameters [19]: the loss coefficient of the channel is 0.2 dB/km, the intrinsic error rate due to misalignment and instability of the optical system is 1.5%, the detection efficiency of the relay (i.e., the transmittance of its optical components together with the efficiency of its detectors) is 14.5%, and the background count rate is 6.02×10^{-6} . (For simplicity, we consider a simplified model of misalignment by putting a unitary rotation in one of the input arms of the 50:50 BS and also a unitary rotation in one of its output arms. The total misalignment value is 1.5%. That is, we assume a misalignment of 0.75% in each rotation.) In comparison, the red curve represents a lower bound on R for an entanglement-based QKD protocol with a parametric down conversion (PDC) source situated in the middle between Alice and Bob [21]. In the red curve, we have assumed that an optimal brightness of a PDC source is employed. However, in practice, the brightness of a PDC source is limited by technology. Therefore, the key rate of an entanglement-based QKD protocol will be much lower than what is shown in the red curve. This makes our new proposal even more favorable than the comparison that is presented in the current Figure.

cret key rate given by Eq. (1) for a realistic setup. Let us tighten up these loose ends here. Indeed, it can be shown that the technique to estimate the relevant parameters in the key rate formula is equivalent to that used in standard decoy-state QKD systems (see Appendix B for details). For simulation purposes, we consider inefficient and noisy threshold detectors and employ experimental parameters from [19] with the exception that [19] considered a free-space channel whereas here we consider a fiber-based channel with a loss of 0.2 dB/km. Moreover, for simplicity, we assume that all detectors are equal (i.e., they have the same dark count rate and detection efficiency), and their dark counts are, to a good approximation, independent of the incoming signals. Furthermore, we use an error correction protocol with inefficiency function $f(E_{\text{rect}}) = 1.16$ [20]. The resulting lower bound on the secret key rate is illustrated in Fig. 2. Our calculations and simulation results demonstrate that the key

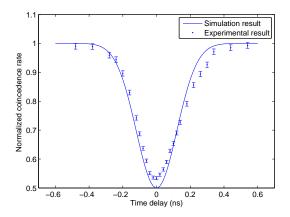


FIG. 3. Hong-Ou-Mandel interference between two phase randomized WCPs. The average photon number is 0.1 per pulse. The coincidence rate is recorded at different time delays. The error bars show the statistical fluctuation (\pm one standard deviation) due to finite data size.

rate is highly comparable to a security proof [21] for entanglement-based QKD protocols. Our scheme can tolerate a high optical loss of more than 40dB (i.e., 200km of optical fibers) when a relay is placed in the middle of Alice and Bob. That is, one can essentially double the transmission distance over a setup where the Bell measurement apparatus is on Alice's side or a setup using a standard decoy-state BB84 protocol [22].

To experimentally implement the MDI-QKD protocol proposed, there are a few practical issues that have to be addressed. Among them, the most important one is probably how to generate indistinguishable photons from two independent laser sources and observe stable HOM interference [17]. Note that the physics behind this protocol is based on the photon bunching effect of two indistinguishable photons at a 50:50 BS. We performed a simple proof of principle experiment to show that a high-visibility HOM interference between two independent off-the-shelf lasers is actually feasible (see details in Appendix C). The results are shown in Fig. 3. The consistency between experimental and theoretical results confirms that a high-visibility HOM dip can be obtained even with two independent lasers.

The idea of MDI-QKD can be generalized much further. First of all, it also applies to the case where Alice and Bob use entangled photon pairs as sources. Second, it works even when Alice and Bob's preparation processes are imperfect. Indeed, basis-dependence that originates from the imperfection in Alice and Bob's preparation processes can be readily taken care of by using a quantum coin idea [12, 18] to quantify the amount of basis-dependent flaw [24]. Third, notice that in practical applications only a finite number of decoy states will be needed. This is similar to standard finite decoy state QKD protocols [25] that have been widely employed in experiments [26]. Fourth, MDI-QKD works even without a refined data analysis. Fifth, it works also

for other QKD protocols including the six-state protocol [27]. These subjects will be discussed further in future publications.

In summary, we have proposed the idea of measurement device independent QKD (MDI-QKD). Compared to standard security proofs, it has a key advantage of removing all detector side channels, and it can double the transmission distance covered with conventional QKD schemes using WCPs. Moreover, it has a rather high key generation rate which is comparable to that of standard security proofs. Indeed, its key generation rate is orders of magnitude higher than the previous approach of full device independent QKD. Our idea can be implemented with standard threshold detectors with low detection efficiency and highly lossy channels. In view of its excellent security, performance and simple implementation, we believe MDI-QKD is a big step forward in bridging the gap between the theory and practice of QKD, and we expect to be widely employed in practical QKD systems in the future.

Notes Added: After the posting of our paper on public preprint servers, another paper by Braunstein and Pirandola [28] has been posted on the preprint servers [29].

Useful conversations with C. H. Bennett, H. F. Chau, C.-H. F. Fung, P. Kwiat, X. Ma, K. Tamaki and Y. Zhao are gratefully acknowledged. We thank N. Lütkenhaus for discussions about Inamori's security proof, C. Weedbrook for comments on the presentation of the paper, and Z. Liao and Z. Tang for helping us in some parts of the experiment. We thank NSERC, the Canada Research Chair Program, QuantumWorks, CIFAR and Xunta de Galicia for financial support.

Appendix A: Security analysis

Here, we show that our protocol for measurement device independent quantum key distribution (MDI-QKD) is unconditionally secure. Our security proof is inspired by that of a time reversed EPR-based QKD protocol [31] and the decoy state method [15]. It can be applied to practical phase randomized weak coherent pulses (WCPs) generated by a laser [32].

In the protocol, each of Alice and Bob uses decoy states and WCPs to prepare the four BB84 states and sends their state to Charles. Charles combines the two signals sent by Alice and Bob and performs a Bell measurement. Afterwards, he announces in a public channel whether he has received a Bell state and which specific Bell state he has received, say, for instance, a singlet state $1/\sqrt{2}(|HV\rangle - |VH\rangle)$. Alice and Bob post-select only those transmission events where Charles has received some specific Bell state.

Using decoy states, Alice and Bob can now obtain the gain and QBER of those events where both of them send to Charlie *single*-photon states. As in GLLP [12], let us consider a *virtual* qubit idea. Instead of preparing a single-photon BB84 state, Alice prepares its purification.

That is to say that one could imagine that Alice actually has a virtual qubit on her side and she prepares her state by first preparing an entangled state of the combined system of her virtual qubit and the qubit that she is sending out in say a singlet state. She subsequently measures her virtual qubit, thus preparing a BB84 state. (Similarly, Bob uses a virtual qubit to help him prepare a single-photon BB84 state.)

Now, in principle, Alice could as well keep her virtual qubit in her quantum memory and delay her measurement on it. Only after Charles has announced that he has obtained a successful outcome (say a singlet), will Alice perform a measurement on her virtual qubit to decide on which state she is sending to Bob.

In such virtual qubits setting, the protocol is directly equivalent to an entanglement based protocol [2, 3, 33]. Alice and Bob share a pair of qubits in their quantum memories and they simply compute the QBER on their virtual qubits in the XX and ZZ bases.

Furthermore, with the above virtual qubit picture in mind, one sees that what Alice and Bob actually send out is unimportant for security proofs as long as their single-photon signals are basis-independent. In the event that there are some basis-dependent flaws in their preparation, Alice and Bob can take care of them by using a quantum coin idea [12, 34]. (Notice that GLLP [12] only considers imperfect state preparation by Alice. Here we are interested in simultaneous imperfections in both Alice and Bob. Nonetheless, with the above virtual qubit formulation, such simultaneous imperfections can still be taken care of by the quantum coin idea. One only needs to consider the fidelity between the combined states sent out by Alice and Bob ρ_{AB}^X and ρ_{AB}^Z , where Alice and Bob both use either the X or Z basis. For a more detailed discussion, see, for example, [34].)

Furthermore, our protocol can tolerate very high channel loss and very low success probability of a Bell measurement without compromising its security. This is because Alice and Bob can post-select only those successful events for a Bell-state measurement by Charles for consideration. Note that Alice and Bob could have implemented their protocol with virtual qubits in their quantum memories and could have waited until Charles announces which Bell-state measurement results are successful. Indeed, in security proofs such as [2] and [3], losses do not affect security.

Appendix B: Estimation procedure

Here we show that the decoy state method [15] applied to MDI-QKD allows Alice and Bob to estimate the relevant parameters to evaluate the secret key rate formula in the asymptotic regime. In particular, they can obtain the gain $Q_{\rm rec}^{1,1}$ and the QBER $e_{\rm diag}^{1,1}$.

Our starting point is the standard decoy state technique applied to conventional QKD. We assume it permits Alice and Bob to estimate the yield Y_n and error

rate e_n of an *n*-photon signal for all n [15]. That is, the set of linear equations

$$Q^{i} = \sum_{n=0}^{\infty} e^{-\mu_{i}} \frac{\mu_{i}^{n}}{n!} Y_{n},$$
 (B1)

$$Q^{i}E^{i} = \sum_{n=0}^{\infty} e^{-\mu_{i}} \frac{\mu_{i}^{n}}{n!} Y_{n} e_{n},$$
 (B2)

with the index i denoting the different decoy settings, can be solved and Alice and Bob can obtain the parameters Y_n and e_n for all n.

In MDI-QKD we have the following set of linear equations:

$$Q_{\text{rect}}^{i,j} = \sum_{n=0}^{\infty} e^{-\mu_i} \frac{\mu_i^n}{n!} e^{-\mu_j} \frac{\mu_j^m}{m!} Y_{\text{rect}}^{n,m},$$
 (B3)

$$Q_{\text{diag}}^{i,j} = \sum_{n,m=0}^{\infty} e^{-\mu_i} \frac{\mu_i^n}{n!} e^{-\mu_j} \frac{\mu_j^m}{m!} Y_{\text{diag}}^{n,m},$$
(B4)

and

$$Q_{\text{rect}}^{i,j} E_{\text{rect}}^{i,j} = \sum_{n=0}^{\infty} e^{-\mu_i} \frac{\mu_i^n}{n!} e^{-\mu_j} \frac{\mu_j^m}{m!} Y_{\text{rect}}^{n,m} e_{\text{rect}}^{n,m},$$

$$Q_{\mathrm{diag}}^{i,j} E_{\mathrm{diag}}^{i,j} = \sum_{n,m=0}^{\infty} e^{-\mu_i} \frac{\mu_i^n}{n!} e^{-\mu_j} \frac{\mu_j^m}{m!} Y_{\mathrm{diag}}^{n,m} e_{\mathrm{diag}}^{n,m},$$

where the indexes i and j represent, respectively, the different decoy settings used by Alice and Bob.

Let us begin with the gain $Q_{\text{rect}}^{i,j}$. This quantity can be written as

$$Q_{\text{rect}}^{i,j} = \sum_{n=0}^{\infty} e^{-\mu_i} \frac{\mu_i^n}{n!} Y_{n;\text{rect}}^j,$$
 (B5)

where

$$Y_{n;\text{rect}}^{j} = \sum_{m=0}^{\infty} e^{-\mu_{j}} \frac{\mu_{j}^{m}}{m!} Y_{\text{rect}}^{n,m}.$$
 (B6)

For j fixed, varying i we have that Eq. (B5) is equivalent to Eq. (B1). This means that Alice and Bob can estimate the parameters $Y_{n;\text{rect}}^{j}$. Once the yields $Y_{n;\text{rect}}^{j}$ are obtained for all j, we have that Eq. (B6) is again equivalent to Eq. (B1) and the legitimate users can estimate the parameters $Y_{\text{rect}}^{n,m}$.

Similarly, it can be shown that Alice and Bob can estimate $Y_{\text{diag}}^{n,m}$.

Let us now focus on the QBER $E_{\mathrm{rect}}^{i,j}$. It can be written as

$$Q_{\text{rect}}^{i,j} E_{\text{rect}}^{i,j} = \sum_{n=0}^{\infty} e^{-\mu_i} \frac{\mu_i^n}{n!} W_{n;\text{rect}}^j,$$
 (B7)

where

$$W_{n;\text{rect}}^{j} = \sum_{m=0}^{\infty} e^{-\mu_{j}} \frac{\mu_{j}^{m}}{m!} Y_{\text{rect}}^{n,m} e_{\text{rect}}^{n,m}.$$
 (B8)

Again, for j fixed, varying i we have that Eq. (B7) is equivalent to Eq. (B1), so Alice and Bob can estimate the parameters $W_{n;\text{rect}}^{j}$. Once these quantities are obtained for all j, we have that Eq. (B8) is equivalent to Eq. (B2) with the yields $Y_{\text{rect}}^{n,m}$ already known. This means that Alice and Bob can estimate $e_{\text{rect}}^{n,m}$.

Similarly, it can be shown that Alice and Bob can estimate $e_{\mathrm{diag}}^{n,m}$.

We have demonstrated that Alice and Bob can estimate the parameters $Y_{\text{rect}}^{n,m}$, $Y_{\text{diag}}^{n,m}$, $e_{\text{rect}}^{n,m}$, and $e_{\text{diag}}^{n,m}$ for all n and m in the asymptotic case; in particular, they can obtain the relevant quantities $Y_{\text{rect}}^{1,1}$ and $e_{\text{diag}}^{1,1}$. Now, the gain $Q_{\text{rect}}^{1,1}$ is given by

$$Q_{\text{rect}}^{1,1} = \mu_A \mu_B e^{-(\mu_A + \mu_B)} Y_{\text{rect}}^{1,1},$$
 (B9)

where μ_A and μ_B denote, respectively, the mean photon number of Alice and Bob's signals.

In practical applications only a finite number of decoy states will be needed. This is similar to standard finite decoy state QKD protocols [25, 35].

Appendix C: Experimental setup of proof of concept experiment

For our idea of MDI-QKD to work in practice, it is important to be able to obtain interference between signals generated by two *independent* lasers (on Alice's and Bob's sides) [36]. Notice that this requirement is at the heart of many quantum information applications such as quantum repeaters, teleportation, qubit amplifiers for device independent QKD, etc. Many investigations and a lot of progress have been made on this subject in recent years (see, e.g., [37] and references therein).

To show that photons from two independent laser sources can be made indistinguishable and interfere with each other, we have performed a simple proof of concept experiment. The experimental setup is shown in Fig. 1. S1 denotes a 1550nm cw fiber laser (NP photonics) and S2 is a wavelength tunable cw laser (Agilent). Both lasers have linewidths less than 1MHz and there is no optical or electrical connection between them. The central wavelength of S2 can be adjusted at steps of 0.1pm (which corresponds to 13MHz at 1550nm). Two optical intensity modulators (IM1 and IM2) are employed to generate narrow laser pulses from the above two cw lasers. Each of these two intensity modulators is driven by an electrical pulse generator (Avtech, PG1 and PG2), which is triggered by a 4-channel delay generator (DG). The time delay between the two laser pulse trains can be adjusted by the delay generator at ps resolution. Two variable optical attenuators (Att1 and Att2) are used to determine the average photon number per laser pulse. An optical phase modulator (PM) is used to scan the phase of one laser pulse train. The two laser pulse trains interfere at a symmetric 2x2 fiber coupler (BS), and the interference signals are detected by two InGaAs singlephoton detectors (SPD, ID Quantique). A time interval

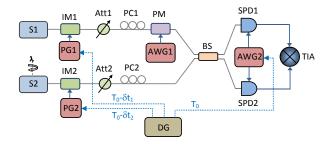


FIG. 4. Experimental setup. S1: 1550nm cw fiber laser (NP photonics); S2: wavelength tunable cw laser (Agilent); IM1-IM2: optical intensity modulators; Att1-Att2: variable optical attenuators; PC1-PC2: polarization controllers; PM: optical phase modulator; BS: 50:50 fiber beam splitter; SPD1-SPD2: single-photon detectors; TIA: Time Interval Analyzer (Picoquant); PG1-PG2: electrical pulse generators (Avtech); AWG1-AWG2: arbitrary waveform generators (Agilent); DG: delay generator (Stanford research systems).

analyzer (TIA, Picoquant) is employed to perform a coincident measurement. The whole system is built upon single-mode telecom fiber based components, thus the spatial modes of the two laser beams are identical. By using two polarization controllers (PC1 and PC2), we can ensure that the two laser pulse trains are in the same polarization state when they interfere at the BS. In this experiment, Alice and Bob are on the same optical table and the fiber length from Alice/Bob to the measurement device is only a few meters.

The pulse shapes of the laser pulses that output from the two intensity modulators have been carefully matched by adjusting the two electrical pulse generators. This shape is approximately Gaussian with a pulse width (FWHM) around 200ps. The corresponding spectral bandwidth is about 5GHz, which is significantly larger than the central frequency mismatch (below 30MHz during the whole experiment). Thus the photons from the

two lasers are indistinguishable in the spectral domain.

The MDI-QKD protocol proposed encodes quantum information in phase randomized WCPs. This means that the phase should be randomly changed from pulse to pulse. This can be achieved by using an optical phase modulator after each laser to introduce a random phase shift from pulse to pulse, as we have demonstrated previously [38]. Here, for simplicity, the phase shift is scanned periodically in the range of $[0,2\pi]$ at 900Hz. In our experiment, the laser pulse repetition rate is 500KHz and one measurement takes about 500s, thus the phase is equivalently randomized.

We measure the Hong-Ou-Mandel (HOM) interference at an average photon number of 0.1 per pulse. During the experiment, at each time delay $\delta_{t_2} - \delta_{t_1}$, we record the detection probability of SPD1 (P_1) , the detection probability of SPD2 (P_2) , and the probability of having a simultaneous "click" in both SPDs within a coincidence window of 2ns (P_C) . The normalized coincidence rate is calculated as $C = P_C/(P_1P_2)$. The experimental results are shown in Fig. 3 of the Main Text of our paper. For comparison purposes, this figure also includes the theoretical results obtained using perfect 200ps Gaussian pulses. The error bars arise from statistical fluctuations (\pm one standard deviation) due to finite data size. The measured HOM dip is 0.534 ± 0.005 . This result confirms that a high-visibility HOM dip can be obtained with independent lasers, thus demonstrating the feasibility of our QKD protocol.

The major error sources in the experiment seem to be the pulse shape mismatch and time jitter. Limited by the equipment available in our lab, PG1 and PG2 are actually two different pulse generators which has limited control over pulse shapes. Other sources of errors are the finite extinction ratio of the intensity modulator, the frequency mismatch between the two lasers, the polarization mismatch, the asymmetry of the BS, the error in determining the average photon number, the dark counts of the SPDs, and statistical fluctuations due to finite data size.

N. Gisin *et al.*, Rev. Mod. Phys. **74**, 145 (2002); V. Scarani *et al.*, Rev. Mod. Phys. **81**, 1301 (2009).

^[2] H.-K. Lo and H. F. Chau, Science 283, 2050 (1999).

^[3] P. W. Shor and J. Preskill, Phys. Rev. Lett. **85**, pp. 441-444 (2000).

^[4] D. Mayers, J. ACM 48 (3), pp. 351-406 (2001).

 ^[5] C.-H. F. Fung et al., Phys. Rev. A 75, 032314 (2007); F. Xu, B. Qi and H.-K. Lo, New J. Phys. 12, 113026 (2010).

^[6] B. Qi et al., Quant. Inf. Comp. 7, pp. 73-82 (2007); Y. Zhao et al., Phys. Rev. A 78, 042333 (2008); L. Lydersen et al., Nature Photonics 4, pp. 686-689 (2010); I. Gerhardt et al., Nature Comm. 2, 349 (2011).

^[7] Instead of receiving quantum signals from Alice through a quantum channel directly, Bob teleports any incoming signal from outside to himself. Provided that Bob has perfect control on the state preparation, he can re-

move all side-channels through teleportation. While this proposal is technologically feasible, a high-performance implementation of teleportation is not without its own challenges [8].

^[8] D. Bouwmeester et al., Nature **390**, pp. 575-579 (1997).

^[9] D. Mayers and A. C.-C. Yao, in Proceedings of the 39th Annual Symposium on Foundations of Computer Science (FOCS98), (IEEE Computer Society, Washington, DC, 1998), p. 503; A. Acín et al., Phys. Rev. Lett. 98, 230501 (2007).

^[10] N. Gisin, S. Pironio and N. Sangouard, Phys. Rev. Lett. 105, 070501 (2010); M. Curty and T. Moroder, Phys. Rev. A 84, 010304(R) (2011).

^[11] H. Inamori, N. Lütkenhaus and D. Mayers, European Physical Journal D 41, pp. 599-627 (2007).

^[12] D. Gottesman et al., Quant. Inf. Comp. 5, pp. 325-360

- (2004).
- [13] C. H. Bennett and G. Brassard, in Proceedings of IEEE International Conference on Computers, Systems, and Signal Processing, Bangalore, India (IEEE Press, New York, 1984), pp. 175-179.
- [14] Note that a key advantage of our work is that Charles' detection system can be arbitrarily flawed without compromising security.
- W.-Y. Hwang, Phys. Rev. Lett. **91**, 057901 (2003); H.-K. Lo, X. Ma and K. Chen, Phys. Rev. Lett. **94**, 230504 (2005); X.-B. Wang, Phys. Rev. Lett. **94**, 230503 (2005).
- [16] H.-K. Lo, H. F. Chau and M. Ardehali, J. of Cryptology 18, number 2, pp. 133-165 (2005).
- [17] C. K. Hong, Z. Y. Ou and L. Mandel, Phys. Rev. Lett. 59, 2044 (1987).
- [18] M. Koashi, on-line available at http://arxiv.org/abs/quant-ph/0505108.
- [19] R. Ursin et al., Nature Physics 3, pp. 481-486 (2007).
- [20] In practice, the effect of the inefficiency function $f(E_{\rm rect})$ on the key rate is very small. Notice that the value $f(E_{\rm rect}) = 1.16$ that we use here is rather conservative. One can achieve better results with, for instance, good error correcting codes. For a given distance, we optimize the intensity of Alice's and Bob's lasers numerically to maximize the key rate. As expected, such intensities are on the order of one.
- [21] X. Ma, C.-H. F. Fung and H.-K. Lo, Phys. Rev. A 76, 012307 (2007).
- [22] The dark count rate affects in a significant way the cut-off point. For instance, if we assume detectors with slightly lower dark count rate like the ones by Gobby et al. [23] (with dark count rate equal to 3.2×10^{-7} and a detection efficiency of 12% (lower than before)), we find that the cut-off point is more than 300km. Our work shows clearly that it is feasible for QKD with WCPs to achieve similar long-distance transmission than what was previously thought [21] to be possible with only entangled states. Furthermore, in contrast to both the protocol of [21] and a standard decoy-state BB84 protocol [15], our new scheme has a tremendous advantage of being immune to all detector side channel attacks.
- [23] C. Gobby, Z. L. Yuan and A. J. Shields, Appl. Phys. Lett. 84, pp. 3762-3764 (2004).
- [24] We thank Kiyoshi Tamaki for enlightening discussions about this point.
- [25] X. Ma et al., Phys. Rev. A 72, 012326 (2005); X.-B. Wang, Phys. Rev. A 72, 012322 (2005).
- [26] D. Rosenberg et al., New J. Phys. 11, 045009 (2009).
- [27] C. H. Bennett *et al.*, IBM Technical Disclosure Bulletin 26, 4363 (1984); D. Bruß, Phys. Rev. Lett. **81**, 3018 (1998).
- [28] S. L. Braunstein and S. Pirandola, on-line available at http://arxiv.org/abs/1109.2330

- [29] Unlike our paper, the manuscript [28] does not consider decoy state or weak coherent pulses. So, it is unclear what key rate it will give. Moreover, the authors of [28] appear to be unaware of previous works by Biham [30] and by Inamori [31]. So, [28] does not discuss about its difference from those important previous papers.
- [30] E. Biham, B. Huttner and T. Mor, Phys. Rev. A 54, 2651 (1996).
- [31] H. Inamori, Algorithmica **34**, pp. 340-365 (2002).
- [32] We remark that our proposal is different from that presented by Biham et al [30] in that it does not require a single photon source or a quantum memory. Instead, Alice and Bob can simply use practical WCP sources. Also, it is different from a proof of security of a reversed EPR-based QKD protocol by Inamori [31] in that it does not demand an almost perfect Bell state measurement and its key generation rate is many orders of magnitude higher than that of Inamori's. Moreover, it was not Inamori's motivation to remove side channels and he did not consider decoy states.
- [33] The intuition of Shor-Preskill's proof [3] is the following. First of all, note that if Alice and Bob share k pairs of singlets (i.e., Alice has one half of each pair and Bob has the other half.), then they can generate a k-bit key that is secure from any eavesdropper, Eve, by measuring their k pairs in the same basis. The key point is that entanglement is monogamous and Eve cannot clone such quantum correlation. Now, suppose two distant parties, Alice and Bob, share a large number, say N of pairs of qubits that are some noisy version of N singlets. They may apply some random sampling procedure to estimate the average state of the qubit pairs that they share, i.e., they can randomly choose a smaller number, say m, of their pairs for testing. Based on the estimated average state. Alice and Bob can then apply a procedure called entanglement distillation protocol (EDP) to distill a smaller number, say k, of qubit pairs that are very close in fidelity to a k-singlet state. Notice that a general EDP requires a quantum computer [2]. Fortunately, Shor-Preskill showed how one can do a special class of EDPs without using a quantum computer. The class of EDPs used by Shor-Preskill involve the separate error correction of two types of errors, namely bit-flip and phase errors.
- [34] K. Tamaki, H.-K. Lo, C.-H. F. Fung and B. Qi, http://arxiv.org/abs/1111.3413
- [35] Y. Zhao, B. Qi, X. Ma, H.-K. Lo and L. Qian, Phys. Rev. Lett. 96, 070502 (2006).
- [36] R. L. Pfleegor and L. Mandel, Phys. Rev. 159, 1084– 1088 (1967); L. Mandel, Rev. Mod. Phys. 71, S274–S282, (1999).
- [37] N. Sangouard, C. Simon, H. de Riedmatten and N. Gisin Rev. Mod. Phys. 83, 33 (2011).
- [38] Y. Zhao, B. Qi and H.-K. Lo, Appl. Phys. Lett. 90, 044106 (2007).